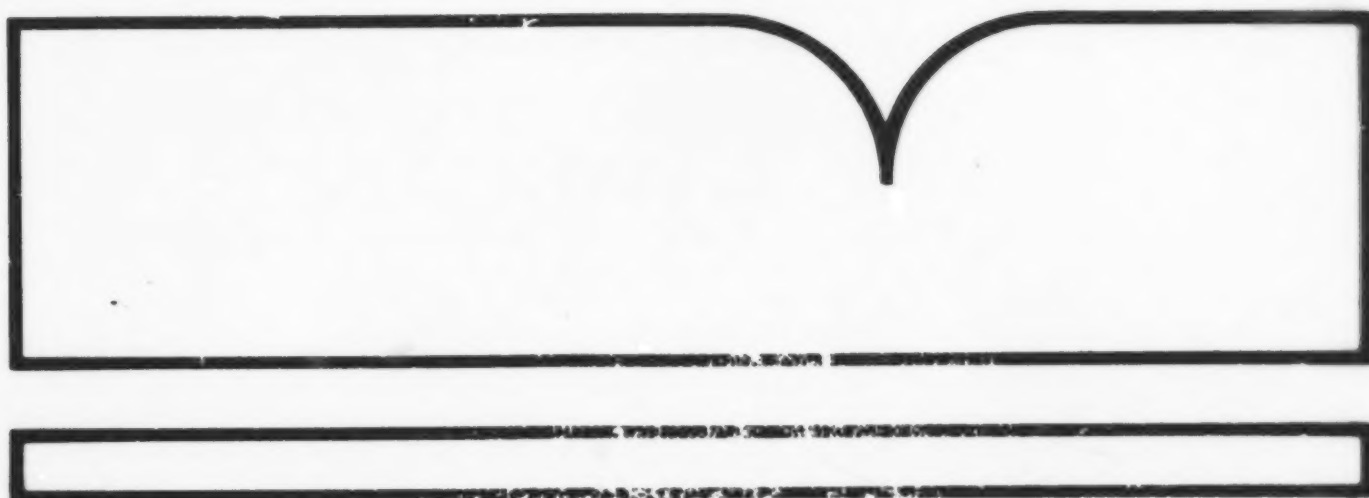


Wind Tunnel Investigation of the Effects of a
Rectangular-Shaped Building on Dispersion of
Effluents from Short Adjacent Stacks

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WIND TUNNEL INVESTIGATION OF THE EFFECTS OF A RECTANGULAR-SHAPED BUILDING ON DISPERSION OF EFFLUENTS FROM SHORT ADJACENT STACKS

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Abstract—In a wind tunnel study, the influence of the highly turbulent region found in the lee of a model building upon plumes emitted from short stacks was examined through smoke visualization and tracer gas concentration mappings. A thick, simulated atmospheric boundary layer was used to provide background dispersion. A rectangular-shaped building with its length equal to twice its height and width was oriented with the long side perpendicular to the approaching wind. The stack was placed midway along the lee side of the building. In all phases of the study, each smoke or tracer release from the stack was repeated with the building removed. This allowed for a simple demonstration of the building wake effects. A simple mathematical model was developed that provided good estimates of concentrations in the building wake. The building influence was found to be reduced with increases in the effective source height. Application of the "2.5 times rule", i.e. an effective source height at 2.5 times the height of the building, resulted in maximum ground-level concentration in the wake being approximately 20 per cent higher than found in the absence of the building. A stack 1.5 times the height of the building resulted in maximum ground-level concentrations in the wake being 250 per cent higher, a far more significant effect.

1. INTRODUCTION

In today's highly industrialized society, means for predicting air quality are important in order to protect the health and general welfare of life. Concentrations of pollutants as emitted into the ambient air are often potentially hazardous. Dilution of these emissions with surrounding air along with the application of control devices is necessary in order to meet ambient air quality standards. Mathematical models that can properly account for dispersion and transport of emissions are an essential element to the development of control strategies.

The entrainment of plumes emitted from short stacks into the wakes of buildings can result in maximum ground-level concentrations that are significantly greater than those found for similar sources in the absence of buildings. In the immediate lee of the building, there is a "cavity" region where recirculation occurs, mean velocities are reduced and the air flow is highly turbulent. The flow in the building wake farther downstream is characterized by a high turbulence intensity and mean velocity deficit that progressively decay to background levels. The outer bound of the wake region is called the "envelope". The complex flow patterns induced by the building prohibit reliable determination of air quality concentrations close to buildings through the use of the basic Gaussian plume model and associated dispersion parameters (Turner,

1970; Pasquill, 1974) without substantial modifications.

The extent of the wake region is undoubtedly a function of building shape and size as well as turbulence levels in the approach flow (e.g. Robins and Castro, 1977a, b; Evans, 1957). A good summary of the current literature is provided by Hosker's (1982) compendium on flow and diffusion near obstacles. Qualitative understanding of flow phenomena near buildings is good. Quantitatively, much less is understood about the effects of buildings as they interact with flow in the atmospheric boundary layer.

There is little consensus as to the best way to estimate ground-level concentrations for plumes that are entrained within building wakes. For situations where the plume is completely entrained into the building cavity, a general form found in the literature for concentration estimates, χ , near the building is given by the equation

$$\frac{\chi U_r}{Q} = \frac{1}{KA}, \quad (1)$$

where U_r is some reference velocity, Q is the source emission rate, A is the projected area of the building and K is a dilution constant. Values of K between 0.5 and 2 are generally suggested.

For sources above the building cavity, estimates of partial entrainment have been proposed wherein a fraction of effluent is mixed uniformly within the cavity (e.g. Halitsky, 1965; Puttock and Hunt, 1979). Concentrations in the region near the building are then

* On assignment from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

estimated by multiplying the fraction by the concentration calculated in (1).

A variety of modifications to the basic Gaussian plume model have been suggested to provide estimates of ground-level concentrations. Gifford (1960) combined the basic Gaussian plume model with (1) to give

$$\frac{zU_r}{Q} = \frac{1}{KA + \pi\sigma_y\sigma_z} \quad (2)$$

where the source height was assumed zero. Very near the building, concentrations are primarily a function of the building area, whereas, far downwind, the building effect becomes insignificant as background dispersion parameters dominate. To account for mixing in the building wake, Turner (1970) suggested that the dispersion parameters for the building wake effects (σ'_y, σ'_z) should be related to the height and width of the building. Virtual source distances X_z and X_y were specified such that

$$\sigma'_z(x) = \sigma_z(x + X_z) \quad (3a)$$

$$\text{and } \sigma'_y(x) = \sigma_y(x + X_y). \quad (3b)$$

Concentrations can then be estimated at downwind distance x by incorporating these adjusted parameters into the basic Gaussian plume model, assuming a source height equal to zero. Alternative modifications have been suggested for elevated sources near buildings where the assumption of zero source height is not valid.

General schemes for estimating effective stack heights for calculating concentrations in building wakes were reported by Lucas (1972) and Briggs (1973). Both suggested that, if the source height is greater than 2.5 times the adjacent building, no correction should be made. A general linear interpolation correction was suggested for a source with a height less than 2.5 building heights. Concentrations can then be estimated by using the adjusted plume height in the basic Gaussian plume model. For Briggs' (1973) scheme, when the estimated plume rise height is less than the estimated cavity height (i.e. 1.5 times the building height), an area-source behavior is suggested, with concentrations estimated in a manner similar to Equation (2). Johnson *et al.* (1975) presented the "split-H" model, so-named because it splits concentrations at a receptor into both a wake entrainment component from ground level, similar to Equation (2), and a component from the effective stack height using the basic Gaussian plume model.

This paper examines building wake effects on short-stack effluents based on an experimental study in a neutral flow wind tunnel designed to provide data for evaluating mathematical models used to estimate concentrations. A rectangular-shaped building with its length equal to twice its height and width was selected. The long side of the building was oriented perpendicularly to the approaching wind. The stack was placed midway along the lee side of the building. Various nondimensional parameters were modeled. A

complete description of these experiments is presented in a laboratory report (Huber *et al.*, 1980). The experimental study consisted of three major phases. In all phases, each case was repeated with the building removed. This allowed for a simple demonstration of wake effects. The design of these experiments is summarized in Section 2. A summary and analysis of the experimental results are presented in Section 3. The experiments were designed to provide a quantitative assessment of the steady-state plume downwind of the fixed source. The scope of the study was limited to one building type and orientation, and one source location. This arrangement was evaluated in only one simulated atmospheric boundary layer. Conclusions and discussion of possible applications and implications of the study are presented in Section 4.

2. EXPERIMENTAL DESIGN

The experimental study was conducted in the Meteorological Wind Tunnel of the U.S. Environmental Protection Agency's Fluid Modeling Facility (Snyder, 1979). The wind tunnel has a test section $3.7 \times 2.1 \times 18.3$ m. The flow speed within the wind tunnel can be controlled between 0.3 and 10 m s^{-1} . In order to ensure that the flow in the model simulates that under full-scale atmospheric conditions, it is necessary to meet certain similarity criteria. Various non-dimensional parameters must be matched in model and prototype. Discussion of similarity criteria can be found, for example, in Snyder (1981).

A method similar to Counihan's (1969), which uses a castellated barrier, elliptic-wedge vortex generators, and surface roughness, was used to produce a thick simulated atmospheric boundary layer. A previous experimental study (Snyder, 1979) showed the boundary layer to maintain equilibrium and uniformity beyond 8 m downwind from the vortex generators. The model building with building height, H_b , equal to 25 cm was placed 9 m downwind from the vortex generators for all experiments except part of those in Phase III, where the building was moved 2.5 m upwind. It is believed that this difference does not have a significant effect on the resulting dispersion pattern downwind of the building. Mean velocity and turbulence intensity measurements taken at the building location ($x = 0$ at downwind edge of building) and at 10 building heights downwind are shown in Fig. 1. Previous experiments showed that a free-stream velocity greater than 1.5 m s^{-1} was necessary for the development of an equilibrium boundary layer.

The depth of the boundary layer, δ , was 1.8 m, so that the ratio of the boundary layer thickness to the building height

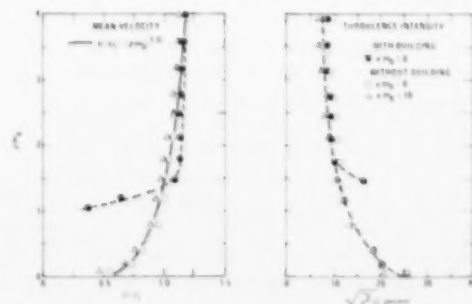


Fig. 1. Velocity and local turbulence intensity measurements, $U_r = 2.34 \text{ m s}^{-1}$ (U_r = reference velocity at $z/H_b = 1.5$).

δ/H_b was 7.1. The velocity profile U/U_r was found to fit a one sixth power law, which is generally representative of neutral atmospheric flow over moderately smooth terrain (Davenport, 1963). The reference velocity, $U_r = 2.34 \text{ m s}^{-1}$, was measured at $1.5 H_b$ above the surface. The local turbulence intensity was 25 per cent near the surface, which is also representative of neutral conditions over moderately smooth terrain (Harris, 1968; Irwin, 1979). For this experimental study, a 1:200 scale model of a 50 m high prototype building would be an appropriate example. On this scale, the wind tunnel boundary layer represents a 360 m deep atmospheric boundary layer. The estimated model surface roughness length (0.065 cm) represents 13 cm in the field, which corresponds to that typical of flow over high grass (Simiu and Scanlan, 1978).

The building Reynolds number, $Re_b = U_r H_b / \nu$, exceeded a value of 36,000 for all experiments reported in this paper, thus assuring a Reynolds-number independent flow based on the minimum building Reynolds number criteria of 11,000 (Snyder, 1981). The stack Reynolds number, $Re_s = W_s D_s / \nu$, where W_s is the stack effluent speed, ranged from 400 to 7500 in these experiments. Hoult and Weil (1972) reported that a value of 300 is sufficient for modeling stack gas effluent situations. To help insure a turbulent effluent stream and thus minimize possible Reynolds number effects, two serrated washers were placed 10 stack diameters upstream from the exit.

Concentrations measured in the model can be related to those that would be measured under similar field conditions. The stack effluent may be assumed to behave as if it were emitted from a point source. Then the field concentration z_f is linearly related to the model concentration z_M , the inverse of

the model emission rate Q_M , the field emission rate Q_f , and to the dilution ratio $U_r H_b^2 / U_f H_{bf}^2$. These basic relations result in the expression

$$\frac{(z_M H_b^2)}{Q_M} = \frac{(z_f H_{bf}^2)}{Q_f} \quad (4)$$

All concentration data are presented in the above non-dimensional form. The velocity at the reference height ($1.5 H_b$) was 85% of the free-stream value. The velocity at all stack height positions (excepting ground-level source, of course) were within 10% of this value. One-minute sampling times were used to determine concentration values. Except in regions where plume entrainment was extremely intermittent, generally stable averages ($\pm 10\%$) resulted. These values correspond to field concentrations over a time period where the background flow remained constant and similar to the model case (on the order of 10 min).

In Phase I the cavity and wake envelope leeward of the building were defined through smoke visualization. Photographs were taken for 30 cases, representing a wide range of source parameters (see Table 1). These cases allow an examination of the differences introduced by changes in the ratios of stack height to building height (H_s/H_b), stack diameter to stack height (D_s/H_s), stack effluent speed to wind speed at stack top (W_s/U_r), stack effluent density to ambient air density (ρ_s/ρ_a) and stack Froude number ($Fr = W_s [g D_s (\rho_s - \rho_a) / \rho_a]^{-1/2}$). Each case was repeated with the building removed, allowing for a simple demonstration of building wake effects.

In Phase II concentration measurements were made in 24

Table 1. Experimental cases

C_{∞} No.	H_s/H_b	D_s/H_s	W_s/U_r	ρ_s/ρ_a	Fr
1	0.0	∞	—	1.0	∞
2	1.2	0.052	0.7	1.0	∞
3	1.2	0.052	0.7	0.5	5.8
4	1.2	0.052	1.5	1.0	∞
5	1.2	0.052	1.5	0.5	13.0
6	1.2	0.052	2.2	1.0	∞
7	1.2	0.052	4.0	1.0	∞
8	1.2	0.052	4.0	0.5	33.4
9*	1.2	0.021	1.5	1.0	∞
10	1.2	0.021	8.4	1.0	∞
11	1.5	0.017	0.4	1.0	∞
12	1.5	0.017	0.4	0.5	11.0
13	1.5	0.042	0.4	1.0	∞
14	1.5	0.042	0.4	0.5	5.8
15	1.5	0.042	0.7	1.0	∞
16	1.5	0.042	0.7	0.5	5.8
17	1.5	0.042	1.5	1.0	∞
17a	2.5	0.025	1.5	1.0	∞
18	1.5	0.042	1.5	0.5	13.0
19*	1.5	0.042	2.2	1.0	∞
20	1.8	0.035	0.7	1.0	∞
21	1.8	0.059	0.7	1.0	∞
22	1.8	0.059	0.7	0.5	4.5
23	1.8	0.091	0.7	1.0	∞
24	1.8	0.091	0.7	0.5	4.2
25*	1.8	0.091	0.4	1.0	∞
26*	1.8	0.091	0.4	0.5	4.2
27*	2.15	0.076	0.7	1.0	∞
28	2.15	0.076	0.7	0.5	4.2
29	2.5	0.065	0.7	1.0	∞
30	2.5	0.065	0.7	0.5	4.2

* No concentration measurements.

of the cases. An air-methane mixture was emitted as a tracer gas and concentrations were measured using a flame ionization detector. Ground-level concentration profiles along the plume centerline were measured to a distance of 15 building heights downwind. Near the point of maximum concentration, vertical profiles were measured. In each case, the profiles were again measured with the building removed. Vertical and lateral concentration profiles through the plume centerline for an isolated stack (no building) situation were also made in one case to characterize dispersion within the simulated atmospheric boundary layer.

In Phase III, for selected cases (Nos 1 and 17) representing strong and moderate building wake effects, additional lateral and vertical profiles were measured within downwind distances of 15 building heights. To examine plume dispersion in the far wake region, concentration measurements within downwind distances of 30 building heights were taken for conditions representing strong, moderate and no immediate building wake effects.

3. EXPERIMENTAL RESULTS

3.1. Observations of smoke plumes

Figures 2 and 3 present the cavity boundary and wake envelope measurements in vertical and horizontal planes of the building, respectively. The cavity size was approximately 3.0 building heights in extent downwind from the lee edge of the building. The

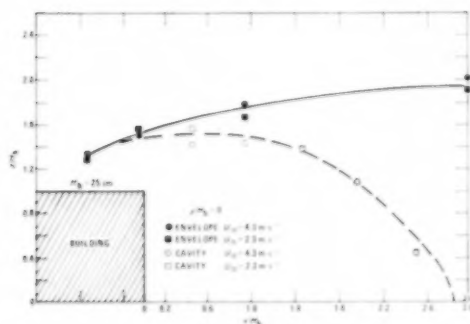


Fig. 2. Vertical wake cavity and envelope measurements.

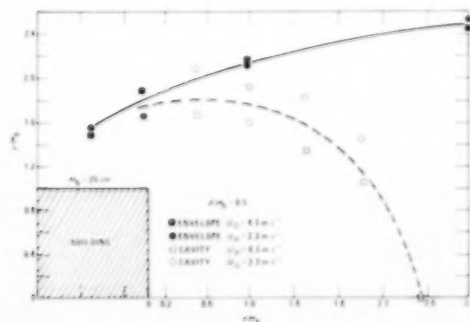


Fig. 3. Lateral wake cavity and envelope measurements.

maximum vertical extent of the cavity region was approximately 1.5 building heights and occurred midway between the leading edge of the building and the downwind end of the cavity. The envelope half-width was slightly larger in the lateral plane. The cavity boundary was determined as the point where no smoke could be seen recirculating back to the base of the building. The wake envelope was determined as the maximum spread of smoke that was emitted from a source within the cavity region. Several other definitions for determining a cavity and envelope region are found in the literature. The choice here was made for its conceptual and experimental convenience.

For the ground-level source, rapid spreading of the effluent was observed to fill the wake in both the vertical and horizontal planes. This resulted from the strong vertical and horizontal recirculation within the cavity region. For low stacks ($H_s/H_b < 1.5$) with insufficient effluent momentum to escape the cavity (Case Nos 2-6, 9 and 11-14), at least partial vertical mixing of the plumes into the wake cavity was observed. Spreading in the horizontal plane, however, was much less rapid than was observed for the ground source. Case Nos 7, 8 and 10 were also of stack heights less than $1.5 H_b$, but, in these cases, the effluent speed was sufficient for the plume to escape the cavity. The major enhancement of the vertical spread of the plume was due primarily to the unsteadiness of the flow over the building. Time-averaged photographs of the plumes are presented in Figs 4 and 5 for the ground-level source and an elevated release. Note that pertinent stack parameters are listed in parentheses after mention of the case number, i.e. (H_s/H_b , D_s/H_b , W_s/U_s , ρ_s/ρ_a). This convention is followed elsewhere to aid the reader. The vertical plume spread depicted by the photographs was similar to that depicted by the vertical concentration profiles of the tracer gas (Huber *et al.*, 1980).

For cases where the effective stack height was above the cavity, there was no entrainment into the cavity, although enhanced vertical dispersion was observed. Decreasing enhancement of lateral dispersion of the plume was observed with increasing effective stack height. Plumes from the most elevated sources ($H_s/H_b = 2.15, 2.5$) were not affected by the building until they naturally spread downward to the wake region. At these downwind distances, the turbulence had significantly decayed from that observed in the cavity of the building. Thus, the overall effect of the wake on the vertical spread of these plumes was smaller.

3.2. Near-field concentrations

Vertical and lateral concentration profiles for the isolated stack (i.e. no building) of Case No. 17 (1.5, 0.04, 1.5, 1) were measured at 5, 10 and 15 building heights downwind, and were used in characterizing dispersion in the simulated atmospheric boundary layer. This case was selected because its plume height was typical of the cases examined and no stack downwash effects were observed. Figures 6 and 7

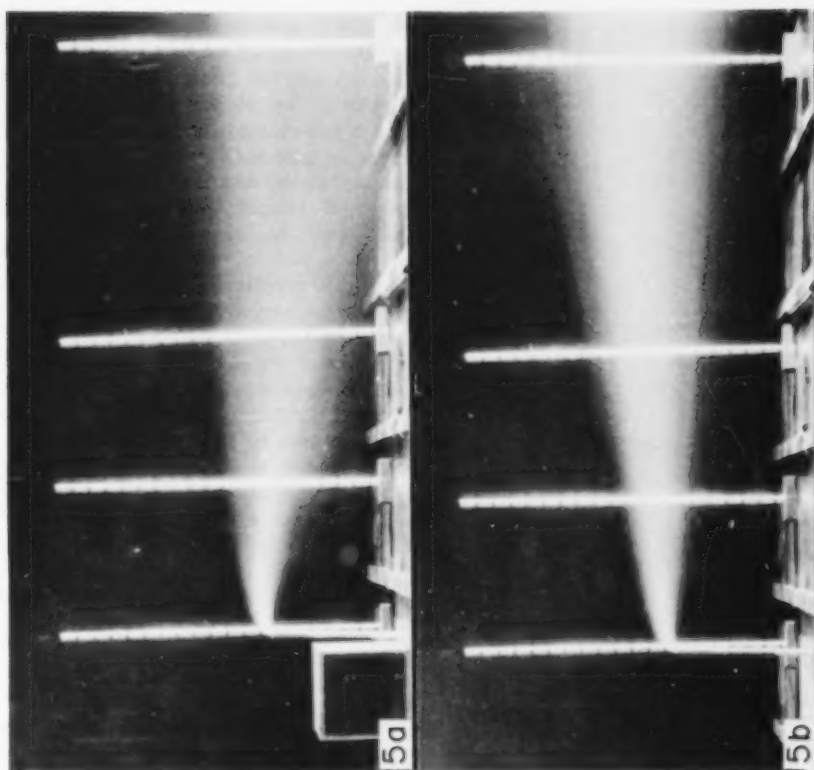


Fig. 5. Case No. 17 (1.5, 0.042, 1.5, 1.0), smoke visualization.

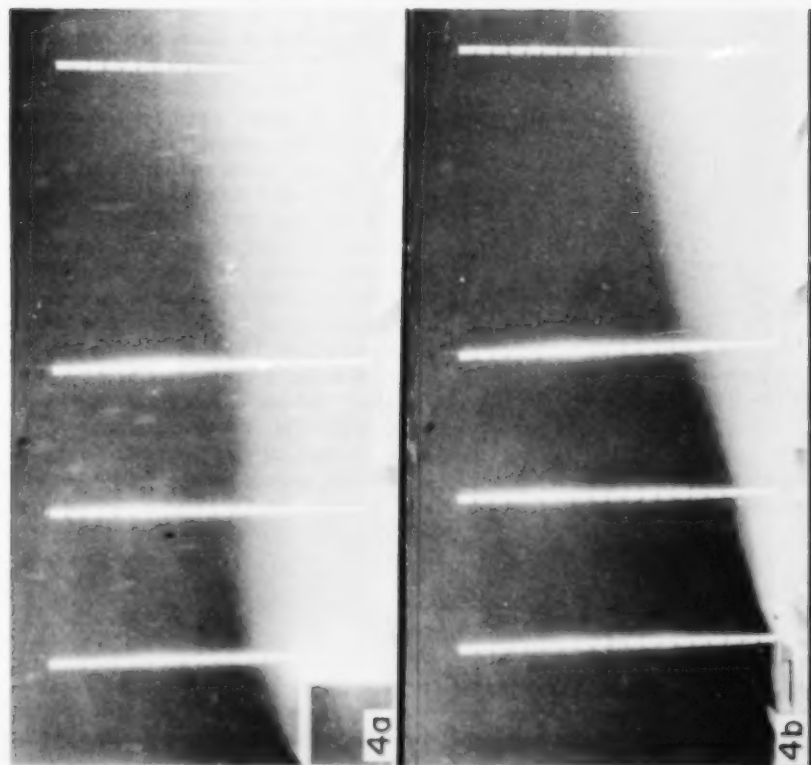


Fig. 4. Case No. 1 (0, α , α , α , 1.0), smoke visualization.

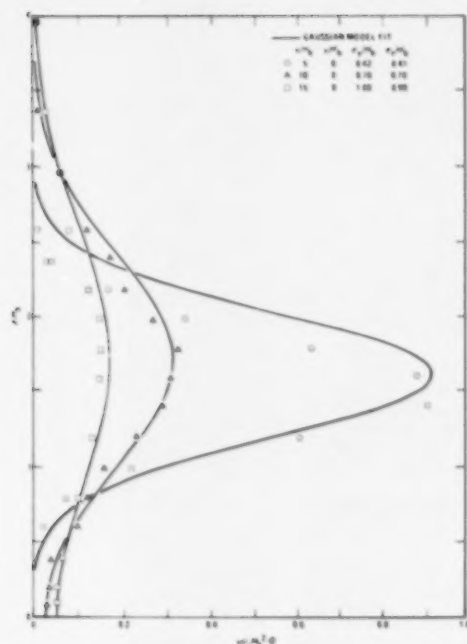


Fig. 6. Vertical concentration profiles taken through the plume centerline; Case No. 17 (1.5, 0.042, 1.5, 1.0), isolated stack.

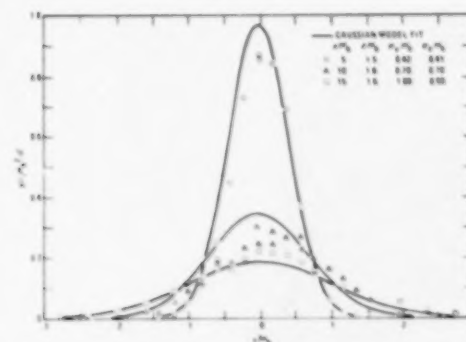


Fig. 7. Lateral concentration profiles taken through the plume centerline; Case No. 17 (1.5, 0.042, 1.5, 1.0), isolated stack.

present the concentration profiles and their estimated Gaussian distributions, expressed as

$$\frac{xU_b H_b^2}{Q} = \frac{\left[\exp\left(-\frac{1}{2} \frac{y^2}{\sigma_y^2}\right) \right] \left\{ \exp\left[-\frac{1}{2} \left(\frac{z-H_b}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2} \left(\frac{z+H_b}{\sigma_z}\right)^2\right] \right\}}{2\pi\sigma_y\sigma_z/H_b^2} \quad (5)$$

Standard deviations σ_y and σ_z were computed from the concentration distributions plotted on normal-probability paper and then slightly adjusted to provide a better fit to the lower half of the vertical profiles, since

this was the region of greatest interest. The above dispersion parameters approximated equally well the vertical concentration profiles for other cases without the building. No additional lateral profiles were measured and thus no further evaluation of lateral dispersion was possible.

The wind tunnel dispersion parameters were compared with the Pasquill-Gifford curves (Turner, 1970). Vertical dispersion within the wind tunnel boundary layer was closest to that for stability C, slightly unstable category. Horizontal dispersion was nearly the same as that for vertical dispersion within the wind tunnel and was closer to that for stability D, neutrally stable category. Of course, the boundary layer flow within the wind tunnel was not truly thermally unstable. A better description of dispersion within the wind tunnel may be that represented by an urban, neutral boundary layer. Dispersion curves (McElroy and Pooler, 1968) based on a diffusion experiment in St. Louis provide a better comparison. The wind tunnel dispersion parameters were closely related to their results under neutrally stable conditions. The dispersion parameters in the wind tunnel were best described by

$$\sigma_z/H_b = \sigma_y/H_b = 0.115 (x/H_b)^{0.8} \quad (6)$$

The effect of the building upon plume rise was evaluated from the vertical concentration profiles. The analysis was limited because only one vertical profile was taken in most cases. Table 2 summarizes the effect of the building wake upon the plume centerline height (vertical position of maximum concentration). For most cases this plume centerline was clearly defined because the profiles were taken close to the source where the maximum was pronounced. Also, these centerline heights represent the final effective height, based on observations and estimates of plume rise (Briggs, 1975). Only Case Nos 7 (1.2, 0.05, 4, 1), 8 (1.2, 0.05, 4, 0.5) and 10 (1.2, 0.02, 8, 1) afforded the opportunity to clearly evaluate plume rise, since for all other cases the rise was minimal. At a position of 10 building heights downwind, the plume rise in the wake of the building was less than two-thirds the value for the isolated stack. This reduction may be a combined result of increased entrainment of the plume by the building wake and excess mean velocity over the building (See Fig. 1). A change of the plume entrainment constants used in the plume rise model could conceivably account for the reduction, but further studies are needed. The lowering of the plume center-

line height both for these cases as well as all other cases may result from a general down-drafting of the plume in the immediate wake of the building. The other cases, although without significant plume rise, did indicate a

Table 2. Summary of effect of building on plume rise

Case No.	$\left(\frac{H_s}{H_b}, \frac{D_s}{H_b}, \frac{W_s}{U_s}, \frac{\rho_s}{\rho_a}\right)$	Longitudinal position of vertical profile (x/H_b)	Vertical position of maximum concentration	
			Isolated stack (z/H_b)	Building (z/H_b)
1	(0.0, ∞ , ∞ , 1.0)	3	0.0	0.0
2	(1.2, 0.052, 0.7, 1.0)	3	1.0-1.2	1.2-1.4
3	(1.2, 0.052, 0.7, 0.5)	3	1.0-1.2	1.1-1.3
4	(1.2, 0.052, 1.5, 1.0)	3	1.3-1.5	1.1-1.3
5	(1.2, 0.052, 1.5, 0.5)	3	1.2-1.4	1.1-1.3
7	(1.2, 0.052, 4.0, 1.0)	10	2.0-2.2	1.6-1.8
8	(1.2, 0.052, 4.0, 0.5)	10	2.0-2.2	1.4-1.6
10	(1.2, 0.021, 8.4, 1.0)	10	2.0-2.2	1.4-1.6
11	(1.5, 0.017, 0.4, 1.0)	3	1.1-1.3	1.1-1.3
12	(1.5, 0.017, 0.4, 0.5)	3	1.1-1.3	0.8-1.0
13	(1.5, 0.042, 0.4, 1.0)	3	1.1-1.3	1.1-1.3
14	(1.5, 0.042, 0.4, 0.5)	3	1.0-1.2	1.1-1.3
15	(1.5, 0.042, 0.7, 1.0)	3	1.3-1.5	1.1-1.3
16	(1.5, 0.042, 0.7, 0.5)	3	1.3-1.5	1.1-1.3
17	(1.5, 0.042, 1.5, 1.0)	6	1.5-1.7	1.3-1.5
18	(1.5, 0.042, 1.5, 0.5)	6	1.5-1.7	1.3-1.5
20	(1.8, 0.035, 0.7, 1.0)	8	1.5-1.7	1.2-1.6
21	(1.8, 0.059, 0.7, 1.0)	8	1.9-2.1	1.5-1.7
22	(1.8, 0.059, 0.7, 0.5)	8	1.7-1.9	1.5-1.7
23	(1.8, 0.091, 0.7, 1.0)	8	1.7-1.9	1.6-1.8
24	(1.8, 0.091, 0.7, 0.5)	10	1.4-1.6	1.5-1.7
28	(2.15, 0.076, 0.7, 0.5)	10	1.9-2.1	1.8-2.0
29	(2.5, 0.065, 0.7, 1.0)	10	2.3-2.5	2.3-2.5
30	(2.5, 0.065, 0.7, 0.5)	10	2.3-2.5	2.3-2.5

slight reduction of the plume centerline height in the wake of the building. In those isolated stack cases where the velocity ratio W_s/U_s was less than 1.5, the plume centerline height was lower than the source height because of downwash in the lee of the stack itself. Downwash was even greater if the effluent density was decreased. A decrease in density resulted in a smaller momentum flux, thus, a smaller immediate plume rise. The effect of changing only the stack diameter was obscured due to scatter in the data and differences in stack Reynolds numbers. Additional study over a far greater range of appropriate stack-source parameters is needed. However, in Fig. 8 at small x , a definite trend toward higher concentrations for decreasing stack effluent speed and stack height is apparent.

Figures 8 and 9 present a sample of the longitudinal ground-level concentration profiles taken in the lee of the building. These are grouped for ease of comparison among the situations influenced by the building wake. Note that for the ground-level source, Case No. 1 (0, ∞ , ∞ , 1), a point was reached where ground-level concentrations were lower than those from elevated stacks (see Fig. 8). This is distinctly different from what occurs from sources in the absence of any building or terrain influences. Normally, the profile from the ground-level source forms an upper-bound or asymptote for a family of curves; profiles from higher sources tend toward this asymptote (from below) at

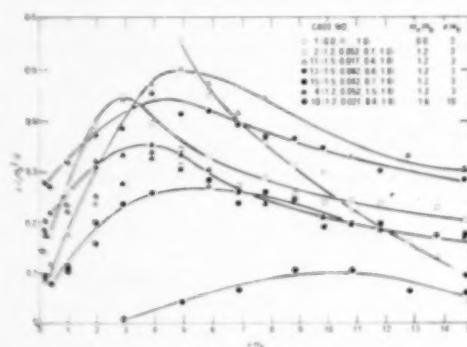


Fig. 8. Longitudinal ground-level concentration measurements in the lee of the building; neutrally buoyant sources with $H_s/H_b \leq 1.5$.

large downwind distances. For the ground source, greater dispersion occurred in both the vertical and lateral directions, which resulted in the lower concentrations downwind. This is in good agreement with the visual observations of the smoke plumes. In the legends of Figs 8 and 9, the effective plume height H_e is the position of maximum concentration as determined from the vertical profiles taken at distance x downwind of the building.

For all the elevated stack cases, the positions of

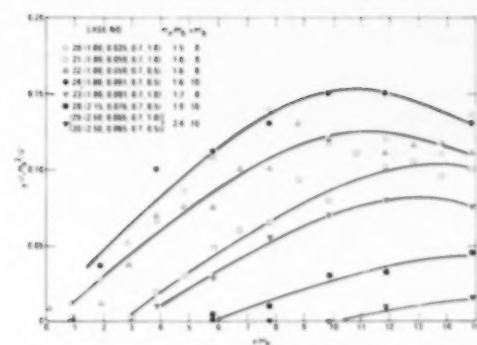


Fig. 9. Longitudinal ground-level concentration measurements in the lee of the building; $H_s/H_b > 1.5$.

maximum ground-level concentration were much closer to the source than were found downwind from the corresponding isolated stacks. In all cases the measured ground-level concentrations out to distances equivalent to $10 H_b$ downwind from the isolated stacks were insignificant as discussed by Huber *et al.* (1980). Thus, ground-level concentrations as presented by Figs 8 and 9 represent concentrations not found in the absence of the building. These results are also in agreement with observations of the smoke plumes. The building significantly enhanced the vertical plume spread. A quantification of this enhancement is described later.

Ground-level concentrations within the cavity region (i.e. $x/H_b \leq 3$) were not uniform. Estimates using Equation (1) imply that K ranges from 1.1 to 5 for the elevated stack cases. Likewise, estimates using Equation (2) downwind of the building imply varying values for K . The effect of changing stack height or effluent parameters appears to have a significant effect on the value of K . The value of K seems to be too sensitive (to all stack and source parameters) to make the use of either (1) or (2) practical.

The shapes of the ground-level concentration profiles are similar to those for elevated releases, as shown by the vertical concentration profiles and visual observations. Thus, it is not realistic to consider plumes from elevated stacks as from ground-level sources. Neither is it realistic to artificially adjust the effective source height solely to force a good estimate of ground-level concentrations. It appears from both the above evaluation of the concentrations and the smoke plumes that a plume from an elevated source in the wake of a building behaves as an elevated release with some adjustment in plume rise due to building and/or stack downwash, and with significantly enhanced vertical dispersion. Good models for estimating concentrations downwind from elevated sources should realistically account for these effects.

A simple model was developed to account for the enhanced dispersion. It was based on two simple concepts: (1) in the immediate lee of the building

(cavity), rapid dispersion occurs and (2) farther downwind, where the flow is reestablishing itself to background conditions, plume spread is controlled by the decaying turbulence. The enhanced plume width σ' was estimated by

$$\frac{\sigma'}{H_b} = [C_1 + C_2(x/H_b)^{C_3}]^{0.5} \frac{\sigma}{H_b}, \text{ for } x/H_b \leq 10. \quad (7)$$

This equation was formulated to evaluate the amplification of plume dispersion as inferred from the ground-level concentration measurements for the ground source (Case 1). The constants C_1 and C_2 were determined from the initial plume spread found at the end of the cavity ($x/H_b = 3$) and much farther downwind where the flow had nearly readjusted to background conditions ($x/H_b = 10$). The constant C_3 reflects the rate at which the flow adjusts itself to background conditions. There are obviously many additional factors which influence plume dispersion. Thus the analysis here may be considered a first-order correction. The rate of decay of turbulence intensity is believed to be the most appropriate measure of the constant C_3 . Measurements of the flow in the wake of the building were not part of this study. The results of a wind tunnel study by Peterka and Cermak (1975) for a similar model building in a similar boundary layer were used to obtain a value of -1.8 for C_3 . These data suggested that

$$\frac{(U_{rms})_{\text{wake}}}{U_r} - \frac{(U_{rms})_{\text{no bldg}}}{U_r} \propto \left(\frac{x}{H_b}\right)^{-1.8}, \quad (8)$$

where the mean velocity U and the root-mean-square velocity U_{rms} were measured at a reference height equal to height of the building. There are other possible relationships for representing the rate of flow readjustment conditions which may be appropriate. However, other values of C_3 (ranging from -1.5 to -2.5) did not significantly affect the results, since the values determined for C_1 and C_2 were compensating. The region between 3 and 10 building heights downwind of the building was chosen to best represent the region for evaluating (7).

The Gaussian plume model using the enhanced dispersion parameters, σ' , (vertical and lateral),

$$\frac{\sigma'}{H_b} = \left[2 + 35 \left(\frac{x}{H_b} \right)^{-1.8} \right]^{0.5} \left[0.115 \left(\frac{x}{H_b} \right) \right]^{0.8} \quad (9a)$$

$$\approx 0.7 + 0.067 (x/H_b - 3), \text{ for } 3 \leq x/H_b \leq 10 \quad (9b)$$

agreed well with the building wake data (Fig. 10). Equation (9b) is a simplified form found to be nearly equivalent to Equation (9a) and has a similar interpretation. The first term represents the initial building influence: the initial plume width (i.e. $2.15\sigma'$) equals the cavity size (i.e. $1.5H_b$). The enhanced vertical and lateral plume widths were assumed equal since visualization and cavity size measurements showed similar behavior in vertical and lateral direction. The second term represents additional growth in the plume width while the flow readjusts to background conditions.

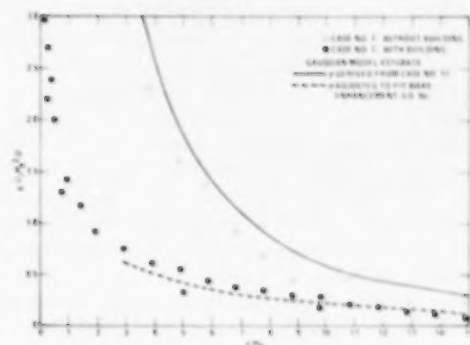


Fig. 10. Longitudinal ground-level concentration measurements for ground source; Case No. 1.

Figure 11 compares model estimates with ground-level concentration data for a wide range of cases having effective stack heights (H_e/H_b) in the wake of the building as summarized in Table 2. For elevated sources, the concentration model estimates were based on modifying only the vertical dispersion parameter, because a significant increase in lateral spread appeared to be absent. Thus, for elevated sources, the model used the enhanced vertical dispersion parameter (9b) and the background horizontal parameter (6). These dispersion parameters along with effective stack height were incorporated into the Gaussian plume model (5). Agreement with the measured values is very good in the range of 3 to 10 building heights and is good from 10 to 15 building heights. There is, as expected, less building influence for the more elevated sources.

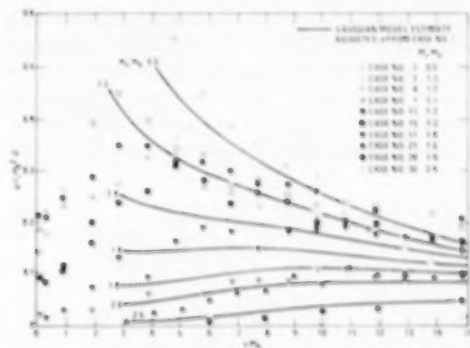


Fig. 11. Longitudinal concentration profiles for several of the elevated stack cases and the ground source; with building.

Figures 12 and 13 present the vertical and lateral concentration profiles for the ground source. Estimates using the modified Gaussian model for the ground source data were good with slightly higher centerline values estimated near the surface at $x/H_b = 5$.

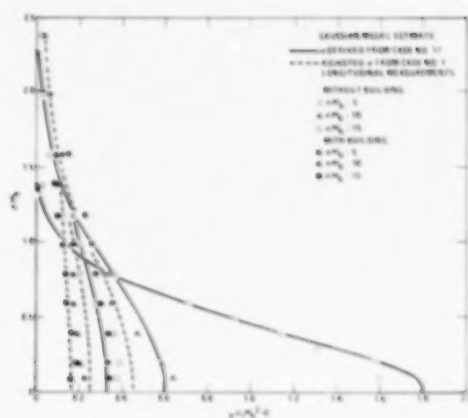


Fig. 12. Vertical concentration measurements for ground source; Case No. 1.

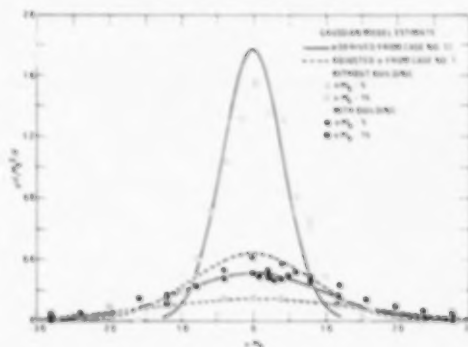


Fig. 13. Lateral ground-level concentration measurements for ground source; Case No. 1.

Vertical and lateral concentration profiles for an elevated source, Case No. 17 (1.5, 0.042, 1.5, 1.0), are compared with the modified Gaussian model in Figs 14 and 15. Profiles for this stack in the absence of the building were presented in Figs 6 and 7. The lower portions of the vertical profiles (Fig. 14) are in agreement with model estimates, but the vertical spread at $x/H_b = 5$ is overestimated; the data show that the plume was contained below about two building heights, whereas the model predicts that the plume will reach three. The lateral profiles (Fig. 15) taken at the elevated levels are in good agreement with model estimates. At ground level, maximum concentrations are predicted quite well, but the horizontal widths of the plumes are considerably underestimated. Perhaps near the ground, influences on the horizontal diffusion must be considered. The correct estimate of vertical diffusion below the plume centerline is the most important factor in determining the ground-level pattern. Neither the ground-level pattern (Fig. 11), nor the vertical profile (Fig. 14) could be so closely matched

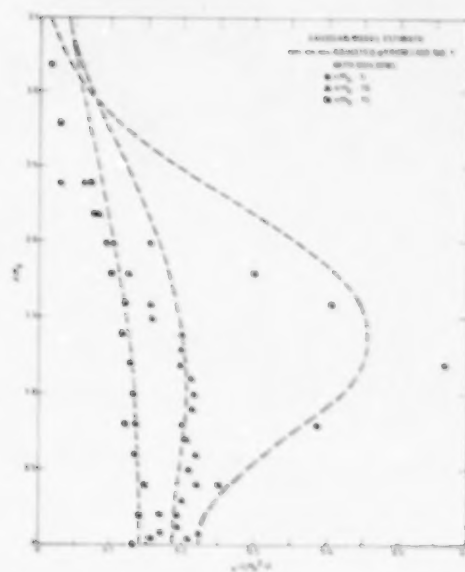


Fig. 14. Vertical concentrations measurements, Case No. 17 (1.5, 0.042, 1.5, 1.0).

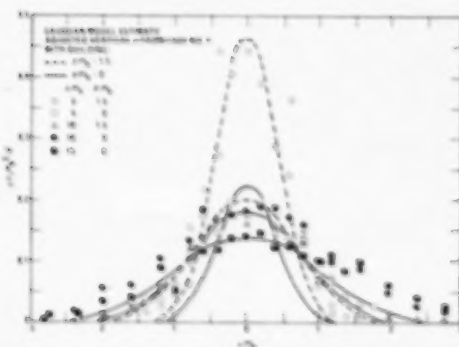


Fig. 15. Lateral concentration profiles, Case No. 17 (1.5, 0.042, 1.5, 1.0).

to the measurements without having good estimates of vertical plume spread. The model does not account for the limited dispersion in the upper portion of the plume. Hence, it should predict excess surface concentrations. Apparently, some enhanced horizontal dispersion and/or additional complexity in the flow compensated for this discrepancy. Additional measurements are needed to examine this question.

3.3. Far-field concentrations

In the near wake region, building wake effects dominate background atmospheric turbulence. The dispersion parameter derived to account for the enhanced dispersion (9b) may possibly be characteristic

of dispersion in the wake of a similar building-stack arrangement, regardless of atmospheric stability. However, it is not likely true for very stable flow and/or all situations with light winds. Far downwind, dispersion is best characterized by the background turbulence; thus, atmospheric stability becomes more important. In effect, the spreading plume far downwind behaves as if it were emitted from a virtual source upwind of the actual source location. Ground-level concentrations were measured to distances 30 building heights downwind in order to evaluate this expectation. Estimated concentrations were made using the Gaussian plume model with dispersion parameters in the far wake ($x/H_0 > 10$) represented by

$$\frac{\sigma'}{H} (x/H_0) = \frac{\sigma}{H_0} (x/H_0 + S) = 0.115(x/H_0 + S)^{0.8}, \quad (10)$$

where S , the virtual source distance in building heights, is a function of the background atmospheric conditions. For the conditions of this study, $S = 8$ as determined by considering the enhanced dispersion found at $z/H_0 = 10$. In general, S would be determined by equating (8) and (10) at 10 building heights, which is the position where the building-induced turbulence no longer dominates the dispersion.

Longitudinal concentration profiles taken to examine the region downwind to 30 building heights are presented in Fig. 16. This figure provides a good overview of the building wake effects on short stack effluents. For the ground-level source, the building wake greatly increased the plume spread (lateral and vertical) in the immediate lee of the building, thus decreasing ground-level concentrations from those that occurred in the absence of the building. Farther downwind, plume dispersion was controlled by the background turbulence. Therefore, the measured concentrations slowly converged to values that occurred in the absence of the building. For the elevated sources, the major building wake effect was that of an increased vertical plume spread, which caused the point of maximum ground-level concentration to shift upwind.

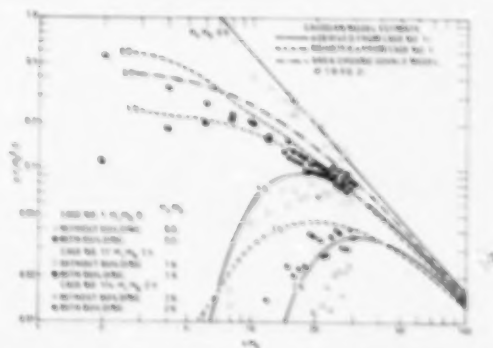


Fig. 16. Longitudinal ground-level concentration measurements, Phase III.

For $H_s/H_b = 1.5$, this effect caused the absolute maximum concentration to increase by 250 per cent over that which occurred in the absence of the building. A similar but much smaller effect was found when $H_s/H_b = 2.5$. For the elevated stack, a convergence of the ground-level concentration to the value measured in the absence of the building was also found to occur in the far-wake region. However, the position of convergence appeared to be somewhat farther downstream.

Model concentration estimates both in the wake of the building and in the absence of the building are also included in Fig. 16. For the two elevated stacks, enhancement of only the vertical plume spread was included. Very good agreement with the model was found for the ground source, Case 1, and elevated source Case No. 17 (1.5, 0.042, 1.5, 1.0). The use of an area-source model (Equation (2) with $K = 1$) provides a good estimate of the ground-level concentrations. For Case 17a (similar to Case 17 but with $H_s/H_b = 2.5$) an overestimate of concentration is seen both in the wake of the building and in the absence of the building. The dispersion parameters used in the model in the absence of the building were estimated from data for a lower stack ($H_s/H_b = 1.5$) and at distances closer than 15 building heights from the source, which may be the cause of the difference. Both the estimated and measured concentrations in the wake of the building are, none-the-less, an indication that the building wake has less effect on the actual maximum ground-level concentrations as the stack height is increased. The model estimates indicate an apparent increase of 20 per cent in the absolute maximum concentration at a stack height of $2.5 H_b$. However, measured concentrations beyond 30 building heights are needed to support this conclusion.

4. CONCLUSIONS

The plume from a ground-level source spread rapidly both in the vertical and lateral directions in the wake of the building. This resulted from the separated, recirculating flow over and around the building that immediately dispersed the effluent plume. Plumes released at or above 1.2 times the building height were similarly enhanced in the vertical but not so much in the lateral direction. Additional lateral profiles are needed to specifically quantify the effect on lateral dispersion. Apparently, such release heights were high enough to avoid the strong lateral unsteadiness and recirculation in the horizontal plane of flow around the building. It appears that the major influence on the spreading plume from an elevated source immediately downwind of the building is enhancement of the vertical component of dispersion. Figure 17 outlines the suggested adjustment to the basic Gaussian model based on evaluation of this study.

Maintaining a ratio of effluent speed to wind speed at stack top 3:2 avoided aerodynamic downwash of the plumes behind the stacks. For the cases with lower

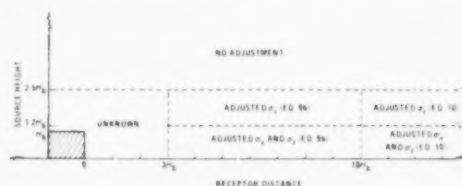


Fig. 17. Suggested use for adjusted dispersion equations.

speed ratios ($W_s/U_s = 0.7, 0.4$), stack downwash was clearly observed. Downwash was even greater if the effluent density was decreased. A decrease in density resulted in a smaller momentum flux, thus, a smaller immediate plume rise. No effects from changing only the stack diameter could be clearly observed. Apparently, any change in momentum flux was offset by a change in the stack wake influence. The effect of changing stack diameter may have been obscured here by the changing stack Reynolds number. Additional study over a wider range of stack-source parameters is needed.

The effective plume centerline height appeared never to be significantly reduced below the emission height because of building wake influences. For the few cases where plume rise was significant, a reduction in plume rise could conceivably be accounted for by increased entrainment constants used in a plume rise model. However, the reduced plume rise may actually be due to general down-drafting of the plume in the immediate wake of the building and/or increased ambient turbulence. In general, it seems that beyond some reasonable distance (e.g. 10 building heights) the net building wake effect on plume spread can be simply accounted for by changing the effective source location, so long as the background plume spread in the absence of the building influence can be characterized.

This study demonstrated that enhanced dispersion is the major building wake effect on stack emissions. An approach that accounts for building wake effects solely by adjusting the source height avoids the real issues of dispersion and plume entrainment in the wake of the building. Dividing the building wake problem into a combined ground source and elevated source problem is somewhat more flexible but deemed inappropriate here. The plumes behaved distinctly as elevated sources. Thus, concentration estimates using a form of Equations (1) or (2) seem appropriate only for ground-level sources. Beyond some reasonable distance down-wind of a building, concentrations estimated by incorporating adjusted dispersion parameters of a form similar to (3a) and (3b) into the basic Gaussian plume model seem appropriate, provided the emission height and stack effluent parameters are known.

The results of this model study are believed to be applicable to similar building shapes in regions of level or gently rolling terrain during periods of steady, near-neutral atmospheric flow. The aerodynamic influences

of the model building discussed above should be generally applicable to other similar situations independent of the wind speed and/or stability of the atmospheric flow, provided that the separated wake is not inhibited. Applications to conditions of very light winds and/or very strong atmospheric stability are most questionable, since such conditions are generally characterized with large horizontal meander of the wind which may have a far greater influence than the building effect examined here. Application to situations in other than level or gently rolling terrain is not appropriate. Application to other block-like buildings should be appropriate provided that the flow over the building is basically three-dimensional. The flow over a very wide or tall building would be two-dimensional except near the ends. The building size and orientation to the wind may significantly affect the scale of plume enhancement. Moreover, corner or horseshoe vortices may be formed when the building is not perpendicular to the wind. These vortices may additionally complicate the flow and plume behavior near the building. The existence and great persistence, although apparently weak, of these vortices has been discussed by Peterka and Cermak (1975), and Robins and Castro (1977a). Their effect on a dispersing plume has not been analyzed. Further studies are needed to evaluate the general applicability of the form of (9) and (10) as estimates of the enhanced dispersion. Surely, in general application, many variables aside from building height and/or width scale have some significance. But as a first-order correction, incorporation of a representative height and/or width scale into these equations may provide quite significant and appropriate corrections to the basic Gaussian plume model.

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